USGS

WATER RESOURCES RESEARCH GRANT PROPOSAL

Title: Development of Multiple Process and Multiple Scale Hydrologic Models

Statement of critical regional water problems

The natural hydrology of south Florida has been extensively altered though channelization to provide adequate water for urban growth and agriculture, and to provide flood protection to the area. Currently, water resource management in south Florida is governed by a number of federal, state, and county agencies. These agencies have developed or adopted hydrologic models to address a diverse set of needs. These range from large-scale models used to estimate impacts of alternative water management practices across all of south Florida, to field-scale models used to predict local impacts such as flooding or agricultural production. At present, there is no feedback mechanism in place for dynamically conveying of information across the wide range of scales addressed by this spectrum of models. Instead, static methods are used, where results from larger-scale models are used as boundary conditions for smaller-scale models. This ignores both the problem of upscaling parameters such as hydraulic conductivity that may be highly variable over small scales, as well as the problem of aggregating a variety of coupled hydrologic processes occurring over a wide range of temporal and spatial scales into a coherent and accurate model of a hydrologic system.

One area of particular interest in south Florida is the C-111 basin in Dade County, which runs from near the city of Homestead south to Florida Bay. This area is located in southern Dade County, Florida. Within the C-111 basin are portions of Everglades National Park and agricultural lands, including those recently acquired by the state of Florida referred to as the ``Frog Pond,'' and urban areas including portions of Homestead and Florida City. This area is bounded on the west by the Everglades National Park and on the east by residential and agricultural lands. As such, it is at the center of competing demands between environmental protection and restoration in Everglades National Park and in flood protection for the agricultural and residential lands.

Statement of the results, benefits, and/or information expected to be gained

This research will result in a greater understanding of the interrelation of hydrologic processes across a range of spatial and temporal scales. A variety of deterministic and stochastic methods for upscaling hydrologic parameters will be investigated and tested. A hydrologic model incorporating a variety of coupled processes and interactions will be developed using domain decomposition and multigrid techniques. The end result of this investigation will be a sophisticated hydrologic model that will be able to predict the effects of changes in water management structures, water management polices, extreme weather events, or gradual changes in weather patterns on urban, agricultural, and natural systems.

Nature, Scope, and Objectives of Research

Goals

This project will investigate how hydrologic processes such as ground water flow, river/canal flow, overland flow, infiltration, evapotranspiration, etc., are manifested across a broad range of spatial and temporal scales. We will focus on the interaction of these processes between scales, as well as understanding how agricultural, urban, and/or natural ecosystems impact-and are impacted by- hydrologic processes at a variety of scales.
The major objectives of this research are to:

- Establish a framework for the efficient exchange and integration of hydrologic information across a wide range of spatial and temporal scales.
- Develop methods for upscaling input parameters and predictions from detailed local models for use in larger-scale sub-regional and regional models.
- Develop a hydrologic model that incorporates these methods and is capable of making predictions over a range of scales.
- Apply this method to areas in southern Florida where agricultural, urban, and environmental interests must share limited water resources.

Background

One of the most challenging aspects of water resource management is the accurate modeling of a wide range of interrelated processes such as ground water flow, infiltration, evapotranspiration, overland flow, river/canal flow, rainfall, etc. Interactions between these processes include the exchange of water between rivers, lakes, and ground water, the relation between the soil moisture content and soil type and the amount of runoff generated from a rainfall event, the partitioning of water in the unsaturated zone between flow into the water table and plant uptake, etc. Even more complexity is added by the large scale of the problem, which can cover hundreds or thousands of square miles, and the fact that the results must be provided to a wide variety of diverse interests. If the appropriate balances between agricultural and urban water use and environmental protection and restoration are to be maintained these processes and interactions must be modeled in a realistic manner. One of the primary difficulties in the development and application of a large-scale hydrologic model is that the relevant processes and interactions occur over a wide range of spatial and temporal scales. This leads to two related issues that must be addressed by the model developer [*Famiglietti and Wood,* 1994] namely, the related matters of scale-dependent spatial variability and aggregation of the various relevant processes over the range of scales.

The first issue arises since hydrologic parameters such as soil type or hydraulic conductivity can exhibit a tremendous amount of spatial variability, in many cases over a range of several different scales. Other driving processes such as rainfall, evapotranspiration, etc., can also be highly variable in time and space. The second issue of aggregation deals with the matter of how to incorporate a variety of hydrologic processes occurring over a wide range of temporal and spatial scales into a coherent and accurate large-scale model of a hydrologic system. We are thus faced with the question: What is the appropriate method to generate a realistic hydrologic model given this complex hierarchy of parameters and scales? Any model that attempts to answer this question must address the problem of how to convey the information produced at one scale and incorporate that information into the model at another scale. It is obvious that such a model will require a complex network of feedback between the relevant processes and interactions over many spatial and temporal scales. Given the amount of information required in a large-scale hydrologic model the solution to this problem is far from straightforward. Efficient communication of the information across the various scales and processes is necessary if a realistic solution is to be obtained at a reasonable cost.

Examples of Hydrologic Models

Traditionally, modeling of large-scale water resources has fallen into two categories: a single model that attempts to encompass a wide range of processes and interactions, or a series of smaller models, each focusing on a specific scale, process (or a limited number of processes), or interaction between processes. An effective use of these models requires linking them together in an appropriate fashion. Most modeling of large-scale hydrologic problems seems fall within the second category since model design and implementation tends to be broken down along the lines of the separate processes modeled. Furthermore, computational constraints (time and/or memory) favor the use of smaller, individual models.
As a gross generalization, hydrologic models can be divided into four scales. Listed from largest to smallest we have:

- Macroscale or General Circulation Models (GCMs).
- Mesoscale or regional models.
- Sub-regional models.
- Local or field-scale models.

The macroscale models/GCMs typically cover the entire earth, or large portions of it, with grid scales on the order of hundreds of kilometers. In addition to modeling of hydrologic processes, GCMs also are used for predicting crop and ecosystem response, climate simulation, modeling of weather processes, etc. Examples of GCMs include the Biosphere-Atmosphere Transfer Scheme (BATS) [*Dickinson* et al., 1993] and the Simple Biosphere Model (1 and 2) (SiB, SiB2) [*Sellers* et al., 1986, 1996a,b].

Regional hydrologic models generally cover portions of a state or several states, i.e., several hundreds to thousands of square kilometers. A primary use of these models is for long-term planning of water resources, which may involve examining the relative impacts of a variety of alternative water management plans, or to model the hydrology of an extended aquifer system. Grid scales are typically on the order of several square kilometers to tens of square kilometers. Examples of regional models include the South Florida Water Management Model (SFWMM), and regional studies of aquifer hydrology by the United States Geological Survey [*Tibbals*, 1990; *Bush and Johnston*, 1988].

Sub-regional models cover areas of catchment or basin size, with grid spacings typically in the hundreds of meters to one or two kilometers. A primary use of these models are for the design of water use and management structures such as canals, levees, pump stations, well fields, etc.

Local or field scale models cover individual farm to sub-catchment scales, with grid spacings ranging from a few tens of meters up to a few hundred meters. These models attempt to predict the impact of water management plans on flooding, runoff, etc at the local scale. Additionally, many models on this scale deal with impacts of land management practices on surface and ground water quality (i.e., fertilizers, pesticides, etc.) Examples include CREAMS [*Knisel*, 1980], GLEAMS [*Leonard* et al., 1986], (see also *Beasley* et al. 1989), FHANTM [*Tremwel and Campbell*, 1992; *Fraisse and Campbell*, 1997], and EAHM [*Savabi*, 1999].

A major weakness of regional and sub-regional models is the scale problem mentioned above. The parameter representations on the large scale are extremely simplified representations of what may be a highly complex and spatially and/or temporally variable parameter over the small scale. For example, hydraulic conductivity can vary greatly over relatively small scales (a few meters to tens of meters), while a large scale-problem may have grid spacings of several kilometers and must use a single averaged value for the parameter. Immediately the problem arises of how to best represent this highly variable parameter with a single averaged value. The success of regional and sub-regional scale models is critically dependent on how well spatially and/or temporally variable parameters are represented at the large scale. Failure to address these issues properly will result in a poor match between model results and reality.

Water Management Models used in South Florida

Currently, water resource management in south Florida is governed by a number of federal, state, and county agencies. The natural hydrology of south Florida has been extensively altered though channelization to provide adequate water for urban growth and agriculture, and to provide flood protection to the area [*Tarboton* et al., 1999]. In order to estimate the system-wide impacts of various alternative water management schemes for planning purposes the South Florida Water Management District uses a large scale (2x2 mile grid) model to simulate the hydrology throughout the region. On the sub-regional scale, the U.S. Army Corps of Engineers uses a model with a 500x500 foot grid spacing to design water control structures such as pump stations, gates, canals, and levees. Results from the large-scale model are used as boundary conditions for this sub-regional model. On the local field scale, models are being developed by the U.S. Department of Agriculture-Agricultural Research Service to predict the impact of water management practices on farm-scale flooding, as well as the impacts of agricultural management practices on surface and ground water quality. These local scale models require canal water levels and water table elevation as boundary information. These data are typically provided by the larger scale models.

At present, there is no feedback mechanism in place for conveying of information across these different scales in a dynamic manner. Rather, a simulation using the large scale model is run to conclusion, and outputs from this are used as boundary conditions for the smaller scale models. Furthermore, there is no way to incorporate information from the smaller scale models back to the larger scale. It is recognized, however, that a formal plan to integrate these models is needed [Forum of Modelers and Agricultural Technical Experts].

One area of particular interest in south Florida is the canal C-111 drainage basin, or simply the ``C-111 basin'' [*Schaffranek*, 1996; *Genereux and Guardiario*, 1998; *Genereux and Slater*, 1999] located in southern Dade County, Florida. The C-111 canal runs from near the city of Homestead to Florida Bay. Within the C-111 basin are agricultural lands recently acquired by the state of Florida and referred to as the ``Frog Pond.'' This area is bounded on the west by the Everglades National Park and on the east by residential and agricultural lands. As such, it is at the center of competing demands between environmental protection and restoration in Everglades National Park and in flood protection for the agricultural and residential lands immediately to the east (Figure 1).

Figure 1. Southern Portion of the C-111 basin and ``Frog Pond'' area. From *Genereux and Guardiario* [1998]

The hydrogeology of the area has been studied by *Genereux and Guardiario* [1998] and *Genereux and Slater* [1999], who have determined transmissivities and hydraulic conductivities through drawdown experiments and examined exchange of water between the canals, aquifer, and adjacent wetlands. Additionally, *Schaffranek* [1996] is working on developing a numerical model to simulate flow and transport in the C-111 basin, with special attention given to understanding the dynamics of water and solute exchange between canals and wetlands.

Work on quantifying vertical exchange of water between ground water and surface water has been done by *Harvey* [1996]. This research also included studies to relate seepage fluxes to subsurface hydrogeologic properties and management of surface-water levels in canals and water conservation areas. A farm-scale deterministic model specific to agricultural interests in south Florida (EAHM) is currently being developed by *Savabi* [1999]. This model will simulate evapotranspiration, percolation, plant growth, infiltration, soil erosion, and the movement of agricultural chemicals within a soil profile.

Domain Decomposition Methods

Over the past several decades, domain decomposition techniques have been developed as a means of solving systems arising from the discretization of linear or nonlinear partial differential equations (PDEs) [*Smith* et al., 1996; *Chan and Mathew*, 1994]. Basically, domain decomposition refers to the process of splitting a problem into several smaller subproblems. This is done for several reasons [*Smith* et al., 1996]: First, it can be used as a method for distributing data from the discretized model among many processors on a parallel computer to solve the large problem much faster than on a computer with a singe processor. This approach can also be used to solve a large problem on a single processor computer that does not have sufficient memory resources to solve a large problem. Second, it can be done to separate the problem into physical subdomains with different processes operating which are modeled with different equations. These two cases are not mutually exclusive, and both of these approaches can be used in a given model.

In both of these cases, the primary technique consists of solving the subproblems at the subdomain level while enforcing appropriate continuity requirements between adjacent subproblems. Although many direct methods have been developed for solving the problems, most recent research in the area has focused on iterative methods, which are also the most applicable to the problem at hand. One large class of domain decomposition algorithms are collectively referred to as non-overlapping algorithms, since the domain is partitioned into non-overlapping subregions. In addition to the usual problem formulation with standard types of boundary conditions, non-overlapping approaches also result in what is termed a {\em transmission boundary condition} on the continuity of the flux of a quantity (such as water, energy, etc.) across the inter-domain boundaries [*Chan and Mathew*, 1994]. The main task in this algorithm is to determine the data, and consequently the fluxes, on the interfaces. At the beginning of the iterative process there are mismatches in the transmitted quantities between the subdomains, but with subsequent iterations the mismatch is reduced until it is below a predefined tolerance.

This technique has great significance for hydrologic problems since one of the fundamental reasons for using a large scale hydrologic model is to determine a water flux into our out of a given region. This can be a flux of surface water, subsurface water, or chemicals across a geographic boundary (e.g., into or out of a canal, across a property boundary, etc.), fluxes of water/chemicals/energy into the subsurface from the surface or into the atmosphere from the surface and subsurface due to evapotranspiration, etc. Accurate determination of these fluxes is important if the model results are to be used to allocate water resources among diverse interests, to help control flooding, and/or to determine the transport of chemicals. Non-overlapping domain decomposition algorithms are ideally suited to modeling this kind of complex interplay of various processes in a large-scale hydrologic model since determination of the fluxes between the subdomains are a fundamental part of the solution process. Furthermore, feedback between domains is an integral part of the iterative solution process. To date, however, only a few workers have taken advantage of domain decomposition methods in solving hydrologic problems [*Beckie* et al., 1993; *San Soucie* 1996].

Multigrid Methods

Multigrid and multilevel techniques [*Briggs*, 1987] are a subclass of domain decomposition methods that have gained widespread acceptance as efficient methods for solving systems of PDEs such as the ground water flow equations [*Beckie* et al., 1993]. Briefly, this method uses a series of nested grids with sequentially larger spacing to solve the system of equations resulting from discretization of PDEs. The rationale behind the development of multigrid algorithms is that when using an iterative method such as Gauss-Seidel technique to solve a PDE, errors with short wavelengths relative to the grid spacing are damped out much quicker than those with longer wavelengths. Consequently, a few iterations are performed at the finest grid spacing, then the current iteration of the solution is transferred up to the next coarsest grid. On this grid, errors that had relatively long wavelengths on the fine grid have shorter wavelengths (again, relative to the coarser grid) and so are damped out relatively quickly. This process is repeated over several different grid scales until an adequate solution is found.

Methods and Procedures

Research Methods

As part of the proposed research we will develop a model that encompasses a variety of hydrologic processes and interactions at different spatial and temporal scales. This model will utilize the domain decomposition and multigrid techniques discussed in the previous section to solve the coupled systems of equations of unsaturated ground water flow, saturated ground water flow, canal flow, and overland flow, and will incorporate infiltration and evapotranspiration effects. We will begin our work by developing the method for the C-111 basin in south Florida, with emphasis on the “Frog Pond” area. This is an ideal test case since it incorporates most if not all of the hydrologic processes discussed above.

We have formulated the following hypothesis to address our research objectives:

Hypothesis: *Domain decomposition and multigrid techniques provide efficient and natural methods for conveying information between different spatial and temporal scales, as well as between physical domains where different processes are operating*.

As discussed previously, domain decomposition and multigrid techniques were developed as a means of efficiently solving a particular PDE governing a particular process, and much of the current research in this area focus on this topic. However, the methodology underlying these methods can be adapted to facilitating the exchange of information between different models at different scales or between subdomains in a single model.

Furthermore, this approach inherently provides dynamic feedback across the various scales since an iterative process is used. This is in contrast to the method currently used in south Florida, where the large grid solution is found first and propagated downward to the smaller scale. This latter method has no natural method of providing feedback back to the larger scale from the smaller scale solution.

Research Tasks

To address the above hypothesis and meet the objectives outlined in the introduction, we have defined four tasks to be accomplished:

Task 1: Develop a detailed hydrologic model of saturated and unsaturated ground water flow, canal flow, overland flow and infiltration, that incorporates rainfall and evapotranspiration. The model will rely on the domain decomposition and multigrid techniques outlined above to ensure that hydrologic information is efficiently communicated across various scales. The model will utilize grid scales ranging from approximately 10 meters up to approximately 4 kilometers.

Task 2: Gather relevant data to parameterize the model for the C-111 basin with emphasis on the Frog Pond area. This will include gathering information on hydrologic parameters such as hydraulic conductivity/transmissivity, soil properties, climatic data, canal operating levels, agricultural land use, crop water use, etc. This will involve meeting and collaborating with researchers from the University of Florida Tropical Research and Education Center (UF-TREC), the U.S. Geological Survey, the South Florida Water Management District, the U.S. Department of Agriculture-Agricultural Research Service, as well as researchers from other universities in Florida.

Task 3: Demonstrate the model by applying it to predict localized (farm-scale) areas of high flood potential within and immediately adjacent to the Frog Pond area. We will utilize a regional scale grid over the entire C-111 basin and telescope down to a local scale grid within the Frog Pond area.

Task 4: Meet with agencies with responsibility for water resource modeling in south Florida (e.g., South Florida Water Management District, U.S. Geological Survey, U.S. Department of Agriculture, U.S. Army Corps of Engineers) to explore the feasibility of utilizing the multi-scale modeling approach developed in this study to integrate the models which currently exist or are being developed for this region.

References

Beasley, D., W.G. Knisel, and A.P. Rice, eds., *Proceedings of the CREAMS/GLEAMS symposium*, Athens, Georgia, Agricultural Engineering Department, University of Georgia - Coastal Plain Experiment Station, 1989.

Beckie, R., E.F. Wood, and A.A. Aldama, Mixed finite element simulation of saturated groundwater flow using a multigrid accelerated domain decomposition technique, *Water Resources Research*, 29(9), 3145-3157, 1993.

Briggs, W.L., *A Multigrid Tutorial*, Society of Industrial and Applied Mathematics, Philadelphia, 1987.

Bush, P. and R.H. Johnston, *Ground-water Hydraulics, Regional Flow, and Ground-Water Development of the Floridan Aquifer System in Florida and in Parts of Georgia,* *South Carolina, and Alabama*, U.S. Geological Survey Professional Paper 1403-C, Washington, 1988.

Chan, T.F. and T.P. Mathew, Domain decomposition algorithms, *Acta Numerica*, 61-143, 1994.

Dickinson, R.E., A.Henderson-Sellers, and P.J. Kennedy, Biosphere-atmosphere transfer scheme (BATS) version 1E as coupled to the NCAR Community Climate Model, Technical Note TN-387+STR, National Center for Atmospheric Research, 1993.

Famiglietti, J.S. and E.F. Wood, Multiscale modeling of spatially variable water and energy balance processes, *Water Resources Research*, 30(11), 3061-3078, 1994.

Fraisse, C.W. and K.L. Campbell, FHANTM (Field Hydrologic And Nutrient Transport Model) version 2.0 user's manual, Research report, Agricultural and Biological Engineering Department, University of Florida, Gainesville, FL, 1997.

Genereux, D. and J. Guardiario, A canal drawdown experiment for determination of aquifer parameters, *Journal of Hydrologic Engineering*, 3(4), 294-302, 1998.

Genereux, D. and E. Slater, Water exchange between canals and surrounding aquifer and wetlands in the southern everglades, USA, *Journal of Hydrology*, 219, 153-168, 1999.

Harvey, J.W., Vertical exchange of ground water and surface water in the Florida Everglades, Fact sheet FS-169-96, U.S Department of the Interior, U.S. Geological Survey, 1996.

Knisel, W.G., CREAMS: A field-scale model for chemicals, runoff, and erosion from agricultural management systems, Conservation Research Report No. 26, U.S. Department of Agriculture, Washington, 1980.

Leonard, R.A., W.G. Knisel, and D.A. Still, *GLEAMS: Groundwater Loading Effects of Agricultural Management Systems*, American Society of Agricultural Engineers, Winter Meeting, Dec. 16-19, Chicago, IL, 1986.

San Soucie, C., *Mixed Finite Element Methods for Variably Saturated Subsurface Flow*, Ph.D. thesis, Rice University, Houston, Texas, 1996.

Savabi, M.R., Determining soil water characteristics for application of a hydrologic model in south Florida. Paper No. 992060, *Presented at the 1999 ASAE Annual International Meeting*, 2950 Niles Road, St. Joseph, MI 49085 USA, {ASAE}, 1999.

Schaffranek, R.W., Coupling models for canal and wetland interactions in the south Florida ecosystem, Fact sheet FS-139-96, U.S Department of the Interior, U.S. Geological Survey, 1996.

Sellers, P., S.O. Los, C.J. Tucker, C.O. Justice, D.A. Dazlich, G.J. Collatz, and D.A. Randall, A revised land surface parameterization (SiB2) for atmospheric GCMs. Part II: The generation of global fields of terrestrial biophysical parameters from satellite data, *Journal of Climate*, 9(4), 706-737, 1996a.

Sellers, P., Y. Mintz, Y. Sud, and A. Dalcher, A simple biosphere model (SiB) for use within general circulation models, *Journal of the Atmospheric Sciences*, 43(6), 505-531, 1986.

Sellers, P., D.A. Randall, G.J. Collatz, J.A. Berry, C.B. Field, D.A. Dazlich, C.~Zhang, G.~D. Collelo, and B.L., A revised land surface parameterization (SiB2) for atmospheric GCMs. Part I: Model formulation, *Journal of Climate*, 9(4), 676-705, 1996.
Smith, B., P. Bjorstad, and W. Gropp, *Domain Decomposition*, Cambridge University Press, New York, N.Y., 1996.

Summary, Forum of Modelers and Agricultural Technical Experts, South Miami-Dade Topographic Interest Group, Homestead, FL, 1999.

Tarboton, K.C., C.J. Neidrauer, E.R. Santee, and J.C. Needle, Regional hydrologic modeling for planning the management of south Florida's water resources through 2050. Presented at the 1999 ASAE Annual International Meeting, Paper No. 992060, ASAE, 2950 Niles Road, St. Joseph, MI 49085 USA, 1999.

Tibbals, C.H., *Hydrology of the Floridan Aquifer System in East-Central Florida*, U.S. Geological Survey Professional Paper 1403-E, Washington, 1990.

Tremwel, T.K. and K.L. Campbell, FHANTM, a modified DRAINMOD: Sensitivity and verification results, ASAE Paper No. 922045, 1992.